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The Natural Resilience of Coastal Systems: Primary Concepts

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Abstract

Coasts are particularly dynamic and the morphology of the coast is continually changing in response to various processes operating at different rates. Coastal landforms are extremely changeable and coastal habitats change over a range of spatial and temporal scales; recognition of these variations is necessary in order that planning and management can be effective. The increasing realisation that human impacts are affecting our coastlines has promoted the concept of vulnerability. Successful management of coastlines, including mitigation of adverse impacts, must be based on an understanding of natural patterns of change. When a trajectory of change is detected, it is often difficult to determine the extent to which it is the outcome of human impact or whether it is part of the natural pattern of change that might have occurred anyway. The complexity and intricacy of the feedbacks surrounding human use of the coast and coastal resources mean that there is rarely consensus on the degree to which human actions have modified natural processes. This chapter examines the patterns, directions and rates of change that coasts undergo. It provides a conceptual basis that underpins any consideration of the extent of human impact. The conceptual framework is illustrated with examples drawn from tropical and subtropical coasts.

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Chapter 4

The Natural Resilience of Coastal Systems: Primary Concepts

Colin D. Woodroffe

Introduction

Coasts are particularly dynamic and the morphology of the coast is continually changing in response to various processes operating at different rates. Coastal landforms are extremely changeable and coastal habitats change over a range of spatial and temporal scales; recognition of these variations is necessary in order that planning and management can be effective.

The increasing realisation that human impacts are affecting our coastlines has promoted the concept of vulnerability. Successful management of coastlines, including mitigation of adverse impacts, must be based on an understanding of natural patterns of change. When a trajectory of change is detected, it is often difficult to determine the extent to which it is the outcome of human impact or whether it is part of the natural pattern of change that might have occurred anyway. The complexity and intricacy of the feedbacks surrounding human use of the coast and coastal resources mean that there is rarely consensus on the degree to which human actions have modified natural processes.

This chapter examines the patterns, directions and rates of change that coasts undergo. It provides a conceptual basis that underpins any consideration of the extent of human impact. The conceptual framework is illustrated with examples drawn from tropical and subtropical coasts.

Vulnerability and Resilience

Vulnerability is the degree to which a coast is likely to be affected by, or its incapability to withstand the consequences of, impact. The impact may be from a natural event, such as a storm or flood, or, as in many of the chapters that follow, it may be from human actions or events. Vulnerability to sea-level rise as a consequence of global climate change has become an issue of international concern. Impacts from other factors associated with

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climate change can also be anticipated, although with less certainty in terms of direction or magnitude. Vulnerability is multi-dimensional, covering natural biogeophysical response of the coast, but also involving economic, institutional and socio-cultural aspects (Klein & Nicholls, 1999). The coast can be viewed as comprising interconnected systems, a natural system and a socio-economic system.

A holistic systems approach incorporates the concept of susceptibility and sensitivity. Susceptibility describes the potential of the system to be affected, whereas sensitivity refers to its responsiveness, how likely it is to change or to fail. Its natural ability to respond can be viewed in terms of the resistance of the coast, which includes mechanical strength of materials, structural and morphological resistance, and its ability to filter the incident energy. Closely related is the concept of resilience, defined as the ability of the coast to resist change in functions or processes (McFadden, Chapter 2). In this chapter, the natural resilience of the coast is the prime focus, but it is important to recognise that similar concepts can be applied to various other aspects of the coastal management process, such as social, cultural, or institutional resilience. Resilience implies the ability of the system to bounce back, or return to some quasi-stable state. This may involve several different, though related factors, allowing a coast to withstand the failures of management, which based as it must be on incomplete understanding, is rarely ideal at protecting coastal resources.

The Coastal System

The study of the mutual co-adjustment of form and process is termed morphodynamics, and underlies our understanding of how and why landforms adjust. Coastal morphodynamic studies have led to development of physical, conceptual, mathematical and simulation models of coastal behaviour. Morphodynamic adjustments occur through the movement of sediment, and the complexity of interacting variables mean that it is useful to adopt a holistic systems approach to the coast. A system involves the interconnection of a series of variables; those within the system are dependent variables, and those outside it are called independent variables, forcing factors or boundary conditions.

Morphological States

A coastal system frequently adopts a particular ‘state’, defined by key parameters, of which morphology is one of the most conspicuous. Coastal landforms often show states that are in an equilibrium, or quasi-equilibrium. The system is maintained at, or more often in the vicinity of, equilibrium by several negative feedbacks and may change between states as a result of changes in boundary conditions. Coastal systems are generally complex non-linear dynamic systems. Equilibria are recognised by persistence of some morphological feature. For example, a beach is an accumulation of loose sand, every grain of which can be moved by the wave energy to which the beach is subject periodically, if not continually. It undergoes changes in shape as an outcome of entrainment and re-deposition of sand, moulding the beachface and associated surf zone into a particular state to either reflect or dissipate the energy of the waves. A beach persists as a result of the tendency for self-organisation through complex feedbacks (Short, 1999).

There has been considerable debate about the extent to which beach shape represents an equilibrium in profile, and in planform. An equilibrium is called 'regime' in the engineering literature, and empirically calibrated rules for the offshore shape of the shallow nearshore profile, and log-spiral shapes for beaches in planform have been proposed. Such an equilibrium is considered an attractor in the language of chaos. It has been described as representative of ecosystem 'health' in terms of the ecology of the system. When monitored over time the shape of a beach is usually found to change subtly, although through a limited number of forms, termed beach states (Figure 4.1).

Beaches adopt one of several states, and sophisticated models have been developed that link beach states with incident wave energy. Initially these models were developed for wave-dominated beaches along the coast of southeastern Australia, incorporating the formation of nearshore bars, changes in beach slope or other parameters. More recently it has been shown that the broad continuum from reflective to dissipative beach states can be applied to beaches around the world (Short, 1999). Beaches undergo change between beach states in response to variations in external factors, such as climate and wave conditions, termed boundary conditions. Figure 4.1 shows schematically the morphological change of a simple wave-dominated beach. The beach in planform lies between two headlands. Its profile can be seen to vary from an accreted form with a pronounced beach berm and a steep beach face (termed reflective because wave energy is predominantly reflected back off the beach face) to an eroded form in which the beach is flatter and a considerable volume of sand has been removed from the beach and is stored in the nearshore in the form of a bar

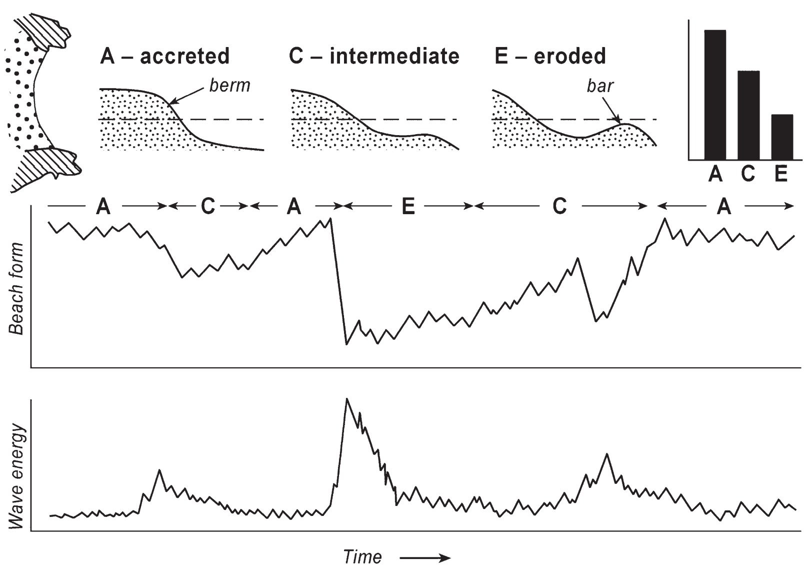

Figure 4.1: Beach morphodynamic concepts illustrated for a schematic beach between headlands. The beach may adopt accreted (reflective), intermediate or eroded (dissipative) states. Its shape, measured by some parameter such as subaerial sand volume, varies in response to wave energy. The response of beaches to wave energy is not immediate, after a storm event during which the beach adjusts to its eroded state there is a gradual recovery.

(termed dissipative because wave energy is dissipated in the surf zone as waves break over the bar). A major storm has the effect of eroding the beach, which adjusts its form to become flatter and builds a nearshore bar that dissipates wave energy. Erosion of the beach occurs during a storm, but that form may persist, and it usually takes weeks or months for the beach to build back to its accreted state. Over time, some beaches that are subject to variable wave energy, fluctuate in response to incident wave energy; as shown schematically in Figure 4.1, and the state which occurs for most of the time, is termed the modal state. More detailed descriptions of these beach morphodynamic models are available in Short (1999).

Types of Equilibrium

If the boundary conditions that affect a beach remained constant then the equilibrium shape of that beach would not be expected to change. It is more often the case for geomorphological systems that external conditions do change and there is a dynamic equilibrium. This is especially true of coastal systems in which sediment is either being deposited or being eroded. Figure 4.2 shows an example of three different beaches each of which adopts a different sort of equilibrium. A sheltered beach may be so immune to changes in wave energy that it remains in a static equilibrium. A more exposed beach may respond, as illustrated in the example in Figure 4.1, by adjusting between an accreted and eroded state, and is termed a metastable equilibrium; one state is found under regular conditions, and a second occurs under a higher energy impetus. Where the volume of sediment on a beach is gradually increasing, as for example where a river supplies sediment to the beach compartment, the beach adjusts in dynamic equilibrium (Woodroffe, 2003).

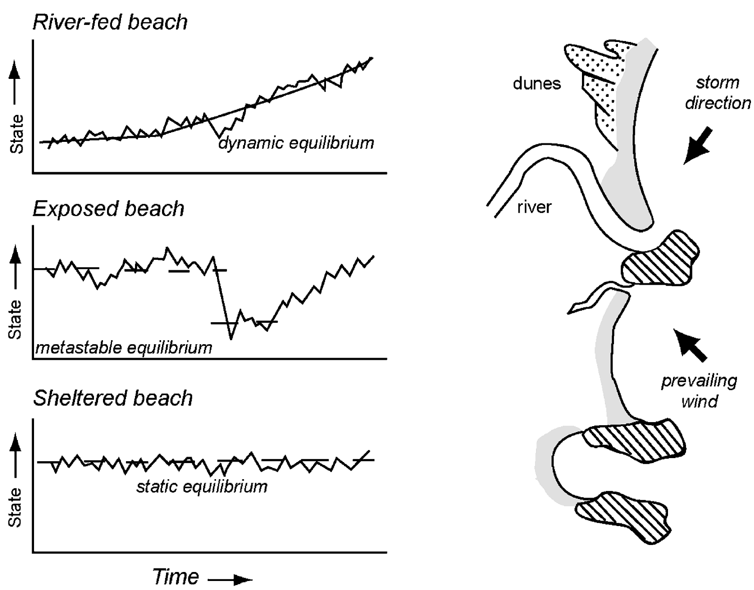

Figure 4.2: Three beaches adopting a different type of equilibrium (after Woodroffe, 2003), see text for details.

The concept of equilibrium is represented by analogy in Figure 4.3, in terms of balls and their movement across a landscape which has a series of depressions. Such an analogy has been widely used in systems literature (e.g. Scheffer, Carpenter, Foley, Folke, & Walker, 2001), where the ball can be thought of as in equilibrium when it is at rest. In a coastal context each ball could be thought of as a pebble on the shore. Simple equilibria can comprise several ideal situations. A stable equilibrium is one in which there appears to be no change and processes are balanced (an attractor); any slight disturbance may move the ball, but it returns, or is attracted, to the bottom of the depression. This is in contrast to an unstable equilibrium (repellor). Unstable equilibria can exist, but the slightest perturbation is likely to disturb the balance and the system then accelerates away from that state; in the case in Figure 4.3 the ball may settle on the top of the crest, but the slightest impulse will result in it rolling away.

Static equilibrium is where no change occurs, and is defined by persistence of the state. Steady-state equilibrium is where boundary conditions do not alter so the system demonstrates stationarity. Some systems adopt a metastable equilibrium, they can occupy two states, but require additional energy to move to their higher energy state; the eroded beach in Figures 4.1 and 4.2 is an example, whereas in the case of pebbles on the shore, it may take a larger wave (energy input) to raise a pebble to a hollow higher on the shore. Dynamic equilibrium is a complex and confusing concept, but it can be thought of as the sort of balance that persists where the shape of the landscape itself is evolving, a situation that is common in geomorphology. The ball in this case is striving to adjust to a moving target (Figure 4.3).

Differences in the Response of Coastal Systems

Any framework within which resilience or vulnerability of the coast is examined, needs to consider several of the key factors influencing the way the physical systems on the coast

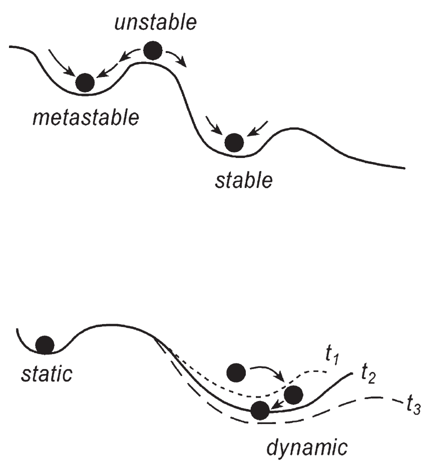

Figure 4.3: The concept of equilibrium. Upper diagram shows stable, unstable and metastable equilibria, lower diagram shows static and dynamic equilibrium.

behave. Adjustments of coastal systems can occur at any of a series of spatial and temporal scales; they occur at varying response times, cross critical thresholds beyond which behaviour changes, and are influenced, in often uncertain ways, by previous sets of conditions. These factors are examined in this section.

Temporal and Spatial Scales

Coastal morphodynamics operate within a hierarchy of temporal and spatial scales (Cowell & Thom, 1994). These are shown schematically in Figure 4.4 with examples from reef systems as an illustration. Time is generally treated as linear and progressive, but in some instances it can be circular, or cyclic. The smallest scale is the 'instantaneous' scale. This is the time frame within which individual waves occur where the physics of fluid dynamics apply (Figure 4.4) and is best examined at a very local spatial scale. At this scale, the linear equations of physics apply and can be expected to have predictive value to the extent that these processes are understood or can be measured. In the case of a reef, the instantaneous scale covers the physical processes beneath an individual wave and the biological processes which enable the coral to grow and so produce sediment (which is the product of the breakdown of the skeletons of coral and other carbonate organisms living on the reef, such as coralline algae, molluscs and foraminifera).

A longer time scale is the 'event' scale, at which a perturbation occurs and the system responds. In the case of reefs it is processes at the event scale, such as tropical storms,

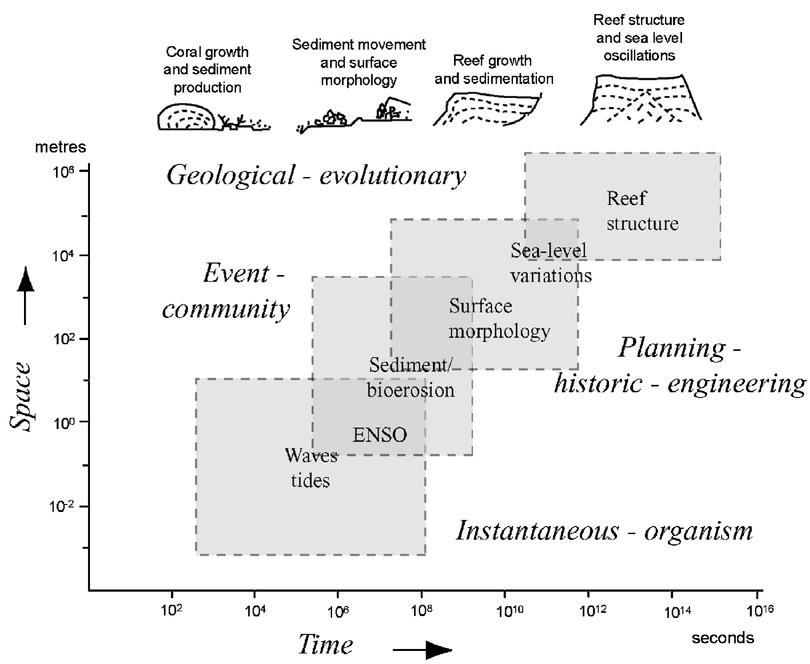

Figure 4.4: Temporal and spatial scales (based on Cowell & Thom, 1994, modified from Woodroffe, 2003), and significant processes on reefs (see text for details).

which have the greatest control on the surface morphology of reefs, detaching and breaking coral colonies and building rubble ridges. The effects of a period of high wave energy have a similar impact on reefs to that shown on beach erosion in Figure 4.1. In Figure 4.1, the beach responds to the storm (high wave energy) by changing state and then recovers from this event towards its pre-storm state (a measure of its resilience). This event scale is described as 'short-term' by Brunsden (2002), and in geomorphology he regards that predictive inferences at this scale are at best informed guesses.

The next level of study concerns regional scales over decades to centuries. In the case of reefs (Figure 4.4), changes at this scale are preserved in the pattern of reef growth and sedimentation. Termed long-term by Brunsden, this is a time scale of particular significance in the context of human societies. It has been variously referred to as the 'historic', 'engineering' or 'planning' time scale (Woodroffe, 2003) because it is the scale over which we know from historical records that there have been changes, and which is of especial significance in terms of planning or engineering projects. Brunsden considers that any attempt to forecast at these scales can be thought of as prophecies, the coastal system's broad behavioural patterns may be known but cannot be predicted with any certainty.

The largest scale is the geological time scale and the global spatial scale. This is the time scale of millennia, extending to millions of years. At this scale there are important broad trends with very significant implications, for example Quaternary variations in sea level have seen significant movements of the shoreline both vertically and horizontally. In the case of reefs, there are remnants of former reefs that grew during previous interglacials and which give valuable insights into tectonic movements, whether uplift or subsidence, and which have constrained our understanding of global climate change. However, the processes at work at these time scales may be imperceptible in the day-to-day management of coastal systems.

Response Time

Time scales become important in the context of forcing functions, or perturbations to the system, termed stresses, or stressors in ecological literature. These are triggering events, representing an energy input to which the system may respond. It is important to recognise several parameters relating to these events, they vary in intensity, duration and frequency; they may be acute, episodic or periodic. Response time to events comprises reaction time, the time it takes for the system to react, and relaxation time, the time it takes for the system to regain its pre-disturbance condition. The average time between events of each magnitude is called the recurrence interval and has a particular significance in terms of whether or not the system has time to recover before there is another event. The reccurrence of events, called event sequencing, can be significant; where one event is followed by another before it has had time to recover, the effect of the second event may then be very different from that of the first. Reaction time, and more particularly relaxation time, may be delayed (lagged). If the system does return to its previous condition then events represent perturbations or pulses, and the system is called intransitive or pulsed (Brunsden & Thornes, 1979; Chappell, 1983). If the system is not stationary in time, and does not recover before the next event, then it is called ramped or transitive, and in this case its post-event condition is different from its pre-event condition.

Time is also important because different things occur at different time scales. Geomorphological changes are usually slow, especially in comparison with most of the time scales of human enquiry, for example monitoring has rarely been carried out for more than a few decades, and 'thesis' time over which intensive studies are carried out is generally only a few years. Other time frames, such as political life (one election term, or one term of office?), human generations, and design time for engineering projects are also short in comparison with the time it has taken for coastal landforms to evolve to their present state.

Incompatibility of time scales can be seen where different disciplines try to come together; for example hydrodynamic adjustments occur in instantaneous time, whereas morphological adjustments, requiring time for the movement of sediment, occur over slower time scales. Many hydrodynamic models are essentially static, they model conditions at the time of observation; dynamic models, which adjust the morphology based on modelling outcomes for process operation, are generally complex and constrained in terms of the time steps they use (see for example van Rijn, 1993).

Models are simplifications that capture the essential behaviour of systems, but they are generalisations and are only indicative, many are probabilistic. Until recently there has been a lack of models for complex non-linear processes, which has hindered detailed quantitative impact assessment. Considerable effort is being made to develop models of large-scale coastal behaviour, attempting to scale up short-term modelling to have greater relevance at longer time scales, but such models are still in their early stages (de Vriend et al., 1993).

Thresholds and Self-Organisation

Thresholds are important steps in system development. A system may pass a threshold in response to external boundary conditions (such as sea level), intrinsic triggers, or a perturbation to the system. Negative feedback (self-regulation) tends to keep a system in, or searching around, an apparent equilibrium. Many systems show positive feedback, or self-organisation, whereby a system may develop along a trajectory of accumulated geomorphological change. Such a trajectory can cross an intrinsic threshold, an abrupt change that occurs without external stimuli.

Figure 4.5 shows a schematic pattern of change on an intermittently open coastal lagoon or barrier estuary. Systems of this type, which are sometimes connected to the sea, but at other times separated from the sea by a sand barrier, are characteristic of the smaller estuaries along the coast of southeastern Australia and in southern Africa. When river discharge is sufficient there is an inlet through which tidal exchange occurs. The tidal processes build a tidal delta with sand accumulating both as an ebb delta on the oceanward side, but more particularly as a flood tide delta on the landward side. Persistent swell activity continues to supply sand to the inlet and during periods of low terrestrial inflow the inlet may close, sealing the coastal lagoon off from the ocean. In the example in Figure 4.5 it is suggested that once the inlet is sealed it requires a higher water level, triggered by a large rainfall event in the catchment, to cross the threshold and reopen the inlet.

There is a tendency for systems to become more organised through time. If a large pile of sand is dumped on a beachface, wave energy is likely to redistribute that sand and to adjust towards an equilibrium beach as described above. The process can be observed as

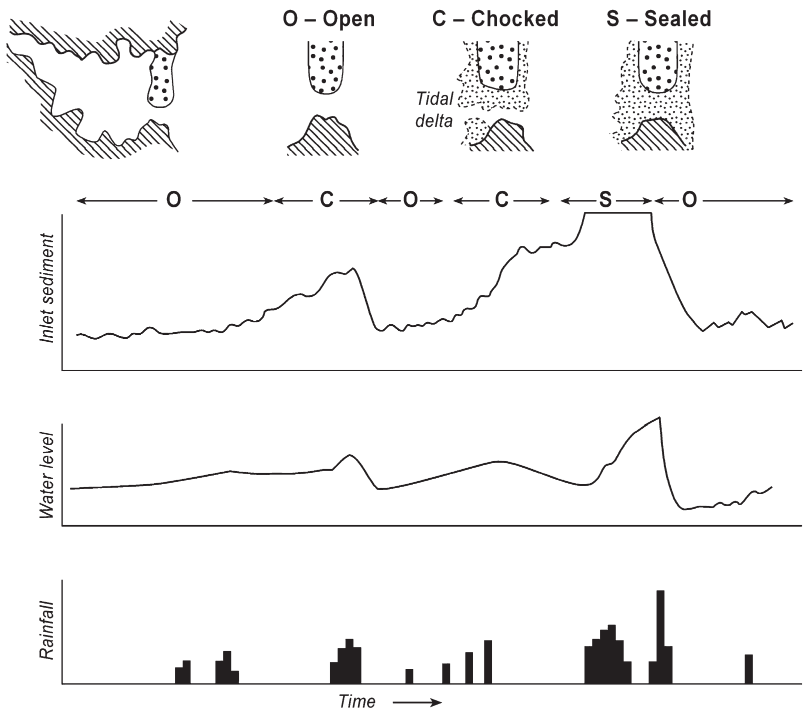

Figure 4.5: Coastal lagoon or barrier estuary, as found along coast of southeastern Australia, showing three states of the inlet or entrance, and a schematic illustration of how that entrance responds to rainfall events and subsequent water level.

the waves rework a sand castle built when the tide is low, and similar processes reshape a beach that has been nourished with sand, as occurs in beach replenishment schemes. If a large pile of very mixed sediment sizes is dumped on the beachface, the various grain sizes become progressively sorted; fine sediment is washed away, sand of similar size to the beach incorporated into the beach, and large boulders left as lag. These processes of organisation can be seen to operate where glacial deposits of highly mixed sediments are reworked by wave action. A striking example is the detailed comparison of sequences of eroding drumlins along the coast of Nova Scotia; mixed moraine from drumlins becomes sorted as the different grain sizes are moved differentially from the cliffed face of the drumlin. Swash-aligned coarse boulder banks develop in front of the cliff face, finer material becomes incorporated into drift-aligned spits, and a self-organised sequence of coastal landforms evolves (Orford, Carter, & Jennings, 1991).

Inheritance and State-Dependence

An important difference between the timeless experiments of physicists or chemists and the landform systems of the geological scientist is that the geological evolution of landforms is time-bound. The state that develops is contingent on events that have gone before. This is generally termed inheritance, or state-dependence. The term sensitive-dependence on initial conditions has become widely used in the language of chaos theory, but this pre-supposes the time-bound laboratory environment in which initial conditions can be defined. Initial conditions cannot be known for the ongoing experiments that nature runs in the real world, increasing the uncertainty about how a coast will evolve (Phillips, 1996). Coastal landforms are often partly contingent on previous landforms or sets of conditions. As a consequence, the evolution of a set of coastal landforms is unpredictable, unrepeatable and irreversible (Cowell & Thom, 1994). The present state is partly an outcome of unique past events; beach states, for example, are not solely a function of contemporaneous wave conditions, but inherit a form from previous wave conditions and beach states. Although there is considerable uncertainty about the details, the broad domain within which the coast operates can be known, providing a range within which probabilistic models can be developed, rather than deterministic models.

In fact, states are re-adopted, but the pathway is often not quite the same in both directions. For example, beaches erode and subsequently recover through a series of intermediate beach states (Figure 4.1). Where the pathway from one state to another takes one route but returns by another, this is termed hysteresis. Formative events are not necessarily extreme events. The critical threshold at which landform change occurs can change over time; for example in a cliff cut into two lithologies, small collapses of the lower lithology may cause the lower strata to retreat to the point where failure in the upper strata occurs, though not in response to one particular extreme event, rather as the outcome of the lower face passing a critical threshold (Brunsden, 2001).

In practice, the coast comprises many complex systems which interact and which may be coupled, as in the cliff collapse example. The pattern of opening and closing of coastal lagoons along the southeast Australian coast and the southern coast of South Africa is more complex than shown in Figure 4.5 and is a function of both conditions to landward in the lagoon, particularly water level, and the state of the beach on the sand barrier (in particular the beach state as indicated in Figure 4.1). Figure 4.6 attempts to capture how these two forcing functions might be coupled. The schematic representation suggests that water level alone may not be sufficient to breach a sealed barrier and reopen an inlet. The behaviour

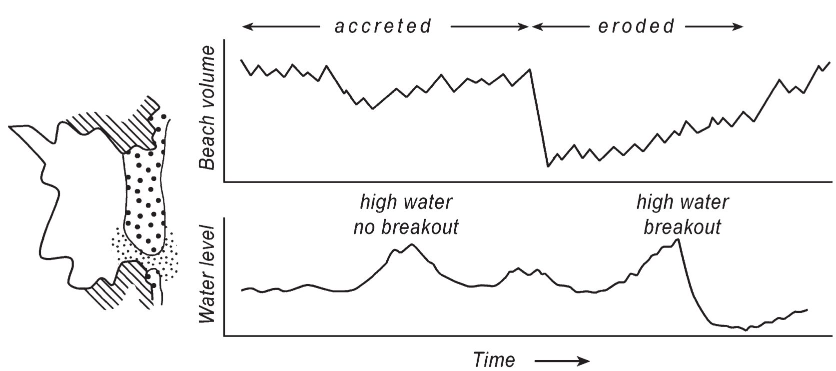

Figure 4.6: Coastal lagoon showing coupling between beach states (as shown in Figure 4.1) and water level (as shown in Figure 4.5).

of the beach is also important; if the beach is accreted then it is less likely to be breached at a critical water level, whereas if it is eroded, the threshold water level at which reopening occurs may be lower. Armouring of a beach represents another example of a time-dependent process that lessens the likelihood of change and alters the threshold at which other adjustments to landforms can occur (Brunsden, 2001).

Equilibrium and the Resilience of Coastal Systems

The existence of conditions that recur or persist, variously termed 'states', 'equilibria' or 'attractors', each having some stability as a result of negative feedback suggests that coastal systems are resilient (Gunderson & Pritchard, 2002). It is possible to identify some subtle differences in how different disciplines have defined a system's resilience and a range of definitions are illustrated schematically in Figure 4.7. Gunderson, Holling, Pritchard, and Peterson (2002) discriminate an engineering and ecological definition, to which is added a geomorphological definition (Brunsden, 2001). The engineering definition involves a measure of the time it takes to return to equilibrium; in Figure 4.7 the steep sided 'attractor' implies a rapid return to equilibrium (resilience). This definition assesses the resistance of the system; an engineering solution such as a seawall is built to resist change. The ecological definition of resilience follows an approach advocated by Holling (1973) who considered it a measure of the ability of a system to absorb changes. It is sometimes measured as the speed of return to the original state (Pimm, 1984). In this case, equilibria are thought

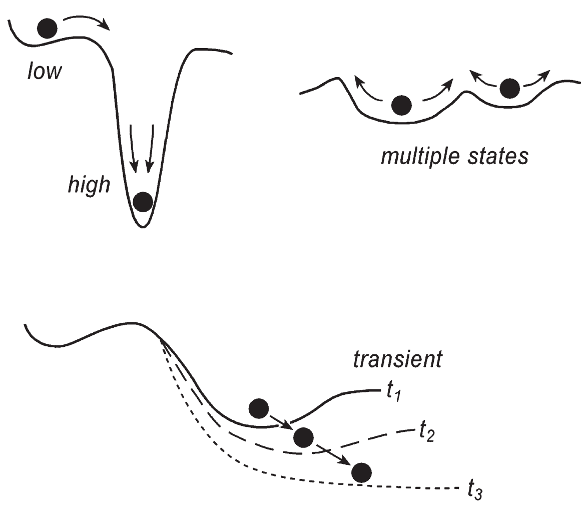

Figure 4.7: Schematic representation of different concepts of resilience. Engineering resilience is shown where structures are designed to be resistant; ecological resilience is where there is elasticity of ecosystems and may involve multiple states (based on Gunderson et al., 2002), and geomorphological resilience involves dynamic systems where the equilibrium may change over time.

of as broad states and resilience involves the breadth of the range over which a system may return to its previous equilibrium state as opposed to adopting an alternative state. Expressed differently, it is the magnitude of disturbance that can be absorbed before the system redefines its structure. Ecological resilience relies on diversity of species, and particularly suites of species that fulfil functional roles; it may deteriorate over time after repeated disturbance (Gunderson et al., 2002).

Coastal and marine ecosystems are often considered in terms of multiple states, and it has been argued that more than one stable community of organisms may be possible in a given habitat (Knowlton, 2004). A change of state, or phase shift, appears to have occurred on coral reefs, suggesting that coral cover, or algal cover may represent alternative stable states (Hughes & Connell, 1999). The significance of this concept for coral reefs is examined below.

Brunsden (2001) has defined geomorphological resilience as the degree to which a system recovers to its initial pre-disturbance state. This recognises that many landform systems strive to reach a dynamic equilibrium, and that the system may not return to an identical state after a disturbance. Brunsden identifies that change between alternative states may be prevented by some barrier to change (the lip of the depression in Figure 4.7), but that this may be transient. Concepts of the elasticity of the system and its malleability are closely linked with this view of resilience. Instead of the static view that is necessary when the engineer is considering the design life of a structure, geomorphologists recognise that landform systems are rarely stationary in time, as boundary conditions change at various time scales. In the case of the coast, sea level is one boundary condition which is known to have changed, and can be anticipated to change in the future. Sea level adjusts at several time scales, and has a profound impact on the coast. This is examined in the coral reef examples discussed below.

Resilience is considered to encompass different things by different researchers, and has been extended to include socio-economic systems. Klein, Nicholls, and Thomalla (2002) have suggested that it has become largely meaningless as a term unless the sense in which it is used is defined. They choose to define resilience in terms of two system attributes, the amount of disturbance a system can absorb and still remain within the same state, and the degree to which it is capable of self-organisation to preserve its actual and potential functions. The term adaptive capacity is widely advocated, as outlined elsewhere in this book, to cover how human adjustments may be incorporated along with the natural variability of the system.

Coral Reefs and the Resilience of Reef Systems

In the case of coral reefs, growth of corals and associated organisms directly influences the morphology of the reef, and reefs can be viewed both as ecological and as geomorphological systems. A coral reef is an accumulation of carbonate, dominated by coral framework, but also incorporating bioclastic sediments derived from other calcareous organisms (coralline algae, molluscs and foraminifera). Coral reefs occur where environmental conditions, such as wave energy, water temperature and water depth are favourable, and the distribution of different growth forms of coral is linked to environmental gradients in light availability, wave energy and sedimentation. Reefs are limited to the photic zone by symbiotic zooxanthellae. In addition to wave energy and nutrient availability, they are constrained in their upper growth by subaerial exposure at lowest tide levels. Corals may be replaced in extremely high wave-energy settings, or at suboptimal water temperatures, by coralline algae. Reefs offer an unparalleled opportunity to examine the nature of past coasts over the full range of time scales identified above as a result of the relatively good preservation of reef limestone and associated sediments (shown schematically in Figure 4.4).

The response of reefs to sea-level change provides an example of the way that a coastal system adjusts to a boundary condition (Figure 4.8), and one that may yield insights into the likely impact of future changes in sea level on reefs. Although individual corals can grow at rates of 10–100 mm a^{-1}, the consolidation of reefal material into a reef occurs more slowly and reef accretion rates vary in the range of 1–10 mm a^{-1}. Where rates of sea-level rise are very rapid, the reef is drowned. At slightly slower rates of rise the reef is likely to backstep, as appears to have occurred in the West Indies around 7 ka BP (Neumann & Macintyre, 1985). If rates of sea-level rise decelerate, the reef has the opportunity to catch up with sea level, as has occurred on much of the Great Barrier Reef (Davies & Montaggioni, 1985). Where the rate of rise is similar or less than the rate of reef growth, a reef can keep up with sea level, as has been the case on the barrier reef in Tahiti (Montaggioni et al., 1997). If sea level is stable, once a reef has reached sea level it will prograde, although several different modes of reef progradation are possible (Kennedy & Woodroffe, 2002). If sea level falls, the reef that has grown up to a higher sea level is left as an emergent reef flat, as is common on many reefs in the Indo-Pacific, explaining the broad reef flat, largely bare of live coral, found on many mid-Pacific atolls (Woodroffe, 2003). Each of these sea-level and reef-growth scenarios can be illustrated

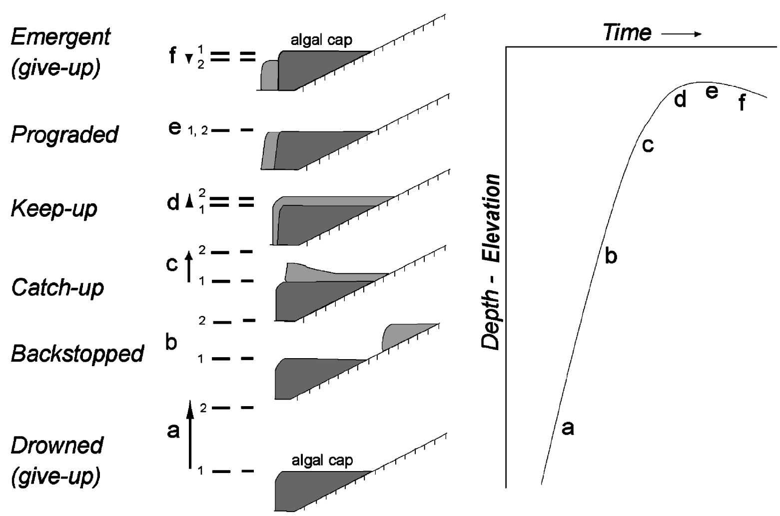

Figure 4.8: Response of reef stratigraphy to sea-level change (after Woodroffe, 2003), see text for details.

by different reefs from around the world, illustrating the range of responses that reef morphology can show to variations in the rate of sea-level change.

In contrast to the view that tropical ecosystems are diverse because they have remained unchanged for millions of years, it is now widely accepted that coral reefs are subject to frequent disturbance. Reefs appear to have adapted to episodic perturbations and demonstrate ecosystem resilience (Brown, 1997). However, it is important to recognise that physical processes and biological processes operate over different time scales (Hatcher, 1997). Thus, while plate tectonics, evolution and mass extinction occur over millions of years, sea-level fluctuations and reef growth are more apparent over millennia (see Figure 4.4). On the other hand, decline of coral reefs through historical time, as a result of human over-exploitation, particularly overfishing, has been exacerbated as a consequence of short-term perturbations, such as individual storms, epidemic disease and El Nino-Southern Oscillation events that recur at shorter time scales than the life history of many of the more massive coral species.

Many reefs appear to be a temporal mosaic of communities at various stages of recovery from these various short-term disturbances (McManus & Polsenberg, 2004). However, the resilience of coral reefs has been called into question in view of an apparent phase shift from coral-dominated reef to one that is dominated by algae. It appears that several types of algal-dominated community (calcareous encrusting algae, low-stature turf algae, calcareous frondose algae, fleshy macroalgae) can exist as alternative states on reefs, but there is concern as to whether coral cover will re-establish, either through regrowth of existing colonies (resheeting) or new recruitment. This has been particularly expressed in relation to Caribbean reefs where a series of separate disturbances, including damage by hurricanes, bleaching as a result of thermal stress, disease and eutrophication, appear to have reduced the capacity of coral to recover (Lesser, 2004). Gradual, but constant, stresses, particularly those resulting from human impacts, may push reefs beyond a resilience threshold.

Reefs appear resilient in view of the robustness shown by their persistence in the geological record. They appear to have coped with major changes of sea level that have completely displaced entire reef structures vertically and horizontally. By contrast with this robustness, reefs also appear fragile and sensitive to changes in environmental conditions (Done, 1999). Widespread coral bleaching, detected on an unprecedented scale around the globe in response to El Niño-related warming in 1998, poses a particular threat to reefs. Bleaching occurs when warmer that usual sea-surface temperatures lead to expulsion of the symbiotic zooxanthellae, and the coral surface becomes pale, in many cases leading to mortality. Global warming, as a result of the enhanced greenhouse effect, poses a particular threat to reefs and there is a vigorous debate over whether reefs are resilient enough to be able to survive (Douglas, 2003). The synergistic effects of various others pressures, particularly human impacts such as overfishing, appear to be exacerbating the stresses on reef systems and, at least on a local scale, exceeding the thresholds beyond which coral is replaced by other organisms.

Summary

A change in the state of a coastal system can occur as a result of one of three factors: (a) a short-term response to a perturbation, (b) as a result of the system passing an intrinsic threshold, or (c) in response to a change in boundary conditions. It is important to understand which of these causes has led to any observed change in natural coastal systems. Coastal systems undergo changes on a range of scales, some of which may be short term, others of which may be lagged responses or intrinsic thresholds. These have been illustrated with examples of beach and coastal lagoon behaviour. Coral reefs leave an incomplete record of past changes within the limestone of the reef, interpretation of which may provide clues to the way that reefal environments have adjusted in the past. Human factors can be, and very often are, associated with changes to the coast. It is important to be able to discriminate between natural adjustment and adjustments that have been exacerbated by human action. It will be crucial to discriminate between a reef's ability to withstand a gradual change in a boundary condition and a more rapid human-induced alteration. Not only will this require a good understanding of how the natural system adjusts, but it will also require scientists to adopt more rigorous adjudication. There are likely to be a wide range of social, cultural and political reasons that obscure the role that humans have had, or are having, in changing the way that coastal systems operate.

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